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Sample Returns Missions in the Coming Decade

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SAMPLE RETURNS MISSIONS IN THE COMING DECADE

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ABSTRACT

In the coming decade, several missions will attempt to return samples to Earth from varying parts of the solar system. These samples will provide invaluable insight into the conditions present during the early formation of the solar system, and possibly give clues to how life began on Earth. A description of five sample return missions is presented (Stardust, Genesis, Muses-C, Mars Sample Return, and Comet Nucleus Sample Return). An overview of each sample return mission is given, concentrating particularly on the technical challenges posed during the Earth entry, descent, and landing phase of the missions. Each mission faces unique challenges in the design of an Earth entry capsule. The design of the entry capsule must address the aerodynamic, heating, deceleration, landing, and recovery requirements for the safe return of samples to Earth.

INTRODUCTION

The first decade of the new millennium will be scientifically very exciting. Currently, five sample returns missions are either in-flight, nearing flight, or being studied which will bring back extra-terrestrial samples to Earth from the solar system for scientific study. These samples will provide invaluable insight into the conditions present during the early formation of the solar system, and possibly give clues to how life began on Earth. These missions are aligned with NASA's Space Exploration Strategic Plan of "Origins, Evolution, and Destiny," trying to answer fundamental questions such as:

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"How did the Universe, galaxies, stars, and planets form and evolve? How can our exploration of the Universe and our solar system revolutionize our understanding of physics, chemistry, and biology? Does life in any form, however simple or complex, carbon-based or other, exist elsewhere than on planet Earth?"[1]

Returned samples from various solar system bodies (comets, asteroids, and Mars) are being considered. The sample return missions are Stardust, Genesis, Muses-C, Mars Sample Return, and Comet Nucleus Sample Return. All these missions baseline land recovery of the samples. Land recovery allows rapid access to the samples for transport to nearby receiving facilities to maintain sample isolation from Earth contaminants.

All these missions propose returning samples to Earth, in lieu of extensive use of sophisticated in-situ instruments in order to remain within stringent program cost and mass limits. The breadth and availability of techniques and equipment that can be employed in a laboratory to analyze the samples are much greater than what can be performed in-flight. Questions spawned from initial investigations can be addressed by additional testing. Furthermore, future technological breakthroughs in analysis capability would allow a re-examination of the samples to further expand scientific understanding, as was possible for lunar samples returned from the Moon. As such, returning samples to Earth provides a greater opportunity of discovery.

This paper gives an overview of each sample return mission, concentrating particularly on the technical challenges posed during the Earth entry, descent, and landing phase of the missions. To remain within stringent program cost and mass limits, each of these missions proposes the use of an entirely passive, spin-stabilized (uncontrolled and unguided) capsule for entry. Each mission employs a different entry scenario (addressing unique mission requirements) for decelerating through the Earth's atmosphere to safely return the samples. The Earth entry velocities for these missions will be higher

(greater than 11.0 km/s) than any previous missions. The resulting high energies associated with each entry drives the capsule design to a blunt aeroshell with an ablating heatshield material for protection from the intense heating environment. This paper describes the aerodynamics, aerothermodynamics, and trajectory requirements of the sample return capsule (SRC) for each mission, and the challenges faced. In addition, the paper presents the landing footprint size for the missions, which must be sufficiently small so as to fit within the proposed area for recovery.

STARDUST MISSION

Stardust, the fourth of NASA's Discovery-class missions, was launched on February 7, 1999 and is currently in-flight. The spacecraft will perform a close flyby of the comet Wild-2. It will come within 100 km of the comet nucleus, and deploy a sample tray to collect cometary and interstellar particles (Fig. 1). Stardust will be the first mission to return samples from a comet. Upon Earth return in January 2006, the entry capsule, containing the comet samples, will be released from the main spacecraft and land by parachute in northwest Utah at the U.S. Military's Utah Test and Training Range (UTTR). A more in depth mission description and the science objectives can be found at http://stardust.jpl.nasa.gov.

Figure 1. Stardust spacecraft sample acquisition flight configuration.

The Stardust SRC (Fig. 2) is approximately 0.8 m in diameter. Its forebody is a blunted 60° half-angle sphere-cone and its afterbody is a 30° truncated cone. The cometary samples are to be collected by extending a collection tray on a boom into the gas/dust freestream emanating from the comet (see Fig. 1), where the particles are to be trapped in a material called aerogel. Once the collection process is completed, the collection tray will be retracted back into the SRC. Reference 2 gives a good overview of the Stardust mission and spacecraft.
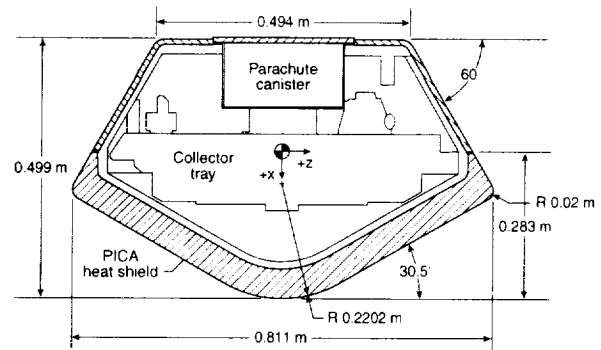

Figure 2. Stardust SRC configuration.

The entry velocity for the Stardust SRC will be the highest (inertial velocity of 12.9 km/s) of any Earth-returning mission to date. For comparison, the Apollo lunar missions had entry velocities of 11.0 km/s. This high entry velocity will result in the highest heating rates for any Earth returning vehicle to date, approximately 1200 W/cm^2 (convective and radiative) at the stagnation point. Traditional carbon-phenolic based thermal protection systems (TPS) are very effective at such intense heating levels; however, they are quite heavy. To remain within mission mass limits, a new lightweight heatshield material is used. This material, Phenolic Impregnated Carbon Ablator (PICA), was developed by NASA Ames Research Center.[3] The predicted heat flux capability of this material is in excess of 1800 W/cm^2. The heating analysis for the Stardust capsule is presented in Reference 4.

Four hours prior to entry, the Stardust SRC will be spun-up and separated from the main spacecraft. The SRC has no active control system, so the spin-up is required to maintain its entry attitude (nominal 0° angle-of-attack) during coast until atmospheric interface. Throughout the atmospheric entry, the passive SRC will rely solely on aerodynamic stability for performing a controlled descent through all aerodynamic flight regimes: hypersonic-rarefied, hypersonic-transitional, hypersonic-continuum, supersonic, transonic, and subsonic. The SRC must possess sufficient aerodynamic stability to overcome the gyroscopic (spin) stiffness in order to minimize any angle-of-attack excursions during the severe heating environment. Additionally, this stability must persist through the transonic and subsonic regimes to maintain a controlled attitude until parachute deployment.

Figure 3 shows the entry sequence developed for the Stardust SRC utilizing a spinning entry as well as drogue and main parachutes (triggered with a g-switch and timers) for descent. At separation, the 46 kg capsule is spun up to 15 rpm for entry. The g-switch is triggered after sensing 3 g's, at which point, the drogue timer is
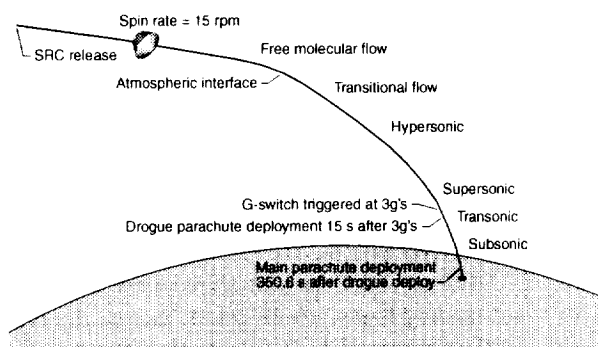
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Figure 3. Stardust SRC entry sequence.

initiated. After 15.04 s, the supersonic drogue chute is deployed (around Mach 1.4), initiating the main timer. After 350.6 s, the main parachute is deployed (around Mach 0.16). The capsule continues the descent until landing. To minimize the heating environment, a fairly shallow entry flight-path angle of $-8.2°$ is utilized. The peak deceleration during the entry is approximately 34 g's.

The high entry spin rate and supersonic drogue parachute were required due to aerodynamic instabilities that were identified for the Stardust SRC. Analysis of the capsule aerodynamics showed that the Stardust SRC was aerodynamically unstable in the free molecular and transonic/subsonic flight regimes due to the aft center-of-gravity location (0.349 body diameters back from the apex of the heatshield) of the capsule.[5,6,7] Trajectory analyses revealed large angle-of-attack excursions during the entry arising from these instabilities.[8,9] If these angle-of-attack excursions are not eliminated or suppressed, a backwards entry attitude or an unsuccessful parachute deployment could result (leading to a loss of the capsule). Unfortunately, the center-of-gravity of the SRC could not be moved forward to eliminate these instabilities. The size and mass of the collection tray precluded large movements in the center-of-gravity.

Since these instabilities could not be eliminated, the entry sequence in Fig. 3 was developed to counter the effects of these instabilities, allowing the Stardust SRC to successfully traverse all flight regimes. The high entry spin rate provides greater gyroscopic stiffness whereby retarding the effects of the free molecular instability. The supersonic drogue chute stabilizes the capsule until main parachute deployment. A high-fidelity six-degree-of-freedom trajectory simulation was developed to substantiate the robustness of the Stardust SRC descent to assure all entry mission requirements are satisfied. References 8 and 9 provide a more detail description of the analysis performed in the development of the entry sequence. The resulting landing footprint for the Stardust SRC is approximately 60

km by 20 km. A footprint less than 90 km is within the easily accessible flat region of UTTR.

GENESIS MISSION

The fifth of NASA's Discovery class missions is a sample return mission known as Genesis. The spacecraft is going through the final checkout phase in preparation for launch in February 2001. It will be the first mission to return samples from beyond the Earth-Moon system. Genesis will be inserted into a halo orbit about the Sun-Earth libration point where it will remain for two years collecting solar wind particles (Figure 4). Upon Earth return in August 2003, the entry capsule containing the solar wind samples, will be released from the main spacecraft (decelerating with the aid of a parachute) for a mid-air recovery over UTTR using a helicopter. Due to the similarities between the Genesis and Stardust missions (i.e., returning a sample capsule to Earth, decelerating with the aid of a parachute, and landing at UTTR), the Genesis entry builds upon the Stardust entry, descent, and landing scenario.[8,9] A more in depth mission description and the science objectives can be found at http://www.gps.caltech.edu/genesis.
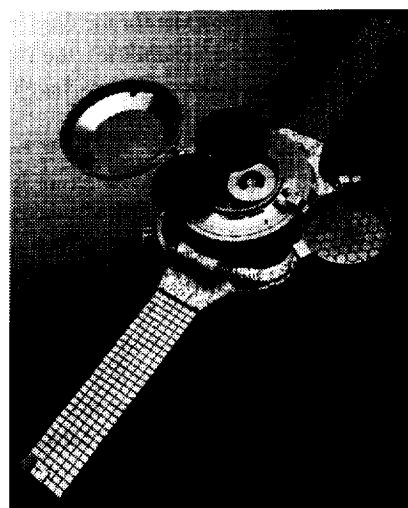

Figure 4. Genesis spacecraft sampling configuration.

The Genesis SRC (Fig. 5) is approximately 1.5 m in diameter. Its forebody is a blunted $60°$ half-angle sphere-cone similar to Stardust. However, the afterbody is very different: Genesis has a bi-conic afterbody with a first cone turning angle of $20°$ and a second cone turning angle of $61.6°$. The solar wind particles will be collected in collector arrays, which are exposed by opening the heatshield. The arrays face the Sun (see Fig. 4), and the particles are trapped in a silica-based material. Once the collection process is completed, the collector arrays will be retracted and the heatshield will be closed.
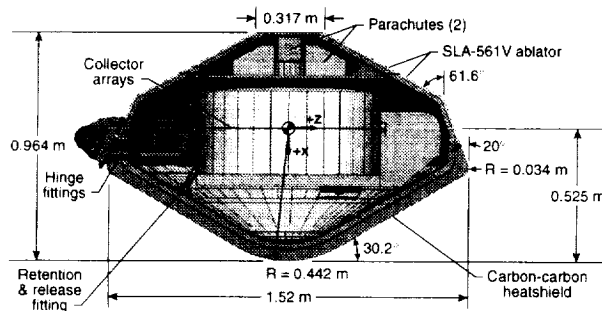
Figure 5. Genesis SRC configuration.

As with the Stardust mission, approximately four hours prior to entry, the Genesis SRC will be spun-up and separated from the main spacecraft. The spin-up maintains the entry attitude (nominal 0° angle-of-attack) during coast until atmospheric interface. Throughout the atmospheric entry, the passive SRC will rely solely on aerodynamic stability for performing a controlled descent through all aerodynamic flight regimes. Genesis has a similar aft center-of-gravity location (0.332 body diameters back from the apex of the heatshield) as Stardust. Consequently, the two instabilities (in the free molecular and transonic/subsonic flow regimes) identified for Stardust, also exist for the Genesis SRC. To counter the effects of these instabilities, the Genesis SRC utilizes the same entry sequence that was developed for the Stardust entry.

A spinning entry is still utilized along with drogue and main parachutes (triggered with a g-switch and timers) for descent. However, the timing of the entry events has been modified. The change was necessitated because the Genesis SRC was found to be more unstable in the transonic/subsonic flight regime due to its different afterbody configuration as compared to Stardust.[10] As a result, drogue chute deployment occurs earlier (around Mach 1.8) to minimize angle of attack excursions near deployment. The Genesis SRC entry sequence is illustrated in Figure 6.
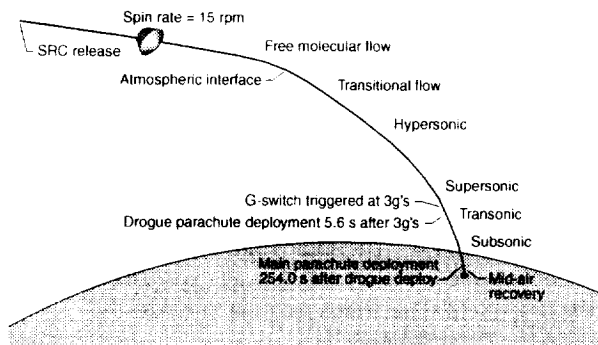

Figure 6. Genesis SRC entry sequence.

At separation, the 210 kg capsule is spun up to 15 rpm for entry. The g-switch is triggered after sensing 3 g's, at which point, the drogue timer is initiated. After 5.6 s, the supersonic drogue chute is deployed (around Mach 1.8), and the main timer is initiated. After 254.0 s, the main parachute is deployed (at around Mach 0.15). The capsule continues its descent until a mid-air recovery is performed with the use of a helicopter at approximately 2.45 km (~8000 ft). Mid-air recovery is baselined to avoid landing loads, which could fracture the brittle silica collector trays. A high-fidelity six-degree-of-freedom simulation was developed to substantiate the robustness of the Genesis SRC descent to assure all entry mission requirements are satisfied. Reference 11 provides a more detailed description of the analysis performed in the development of the entry sequence. The resulting entry footprint for the Genesis SRC is approximately 55 km by 20 km, which is within capability of the UTTR landing area.

The inertial entry velocity for the Genesis SRC will be 11.0 km/s, significantly lower than that for the Stardust entry. The peak deceleration during the entry is approximately 28 g's. A fairly shallow entry flight-path angle of $-8.0°$ is utilized to minimize the heating environment. At the stagnation point, the peak heat rate is approximately 500 W/cm^2, which corresponds to a heat load of 16.8 kJ/cm^2. PICA was originally carried over from Stardust as the baseline heatshield material. However, since the Genesis SRC is approximately twice as large as Stardust, the heatshield could not be manufactured in a single piece. Concerns about heating at the seams of the segmented design led to a change in the heatshield material to a 2-D carbon-carbon fabric over carbon fiberfoam.

While the Stardust SRC is attached to the spacecraft through its afterbody, the Genesis SRC is attached to the main spacecraft via three attachment points in the forebody heatshield. There was concern that these penetrations could induce transition to turbulent flow for some region aft of the cavities. As a result, a detailed heating analysis in the vicinity of the attachment points was conducted to assess the likelihood of transition to turbulence during the heat pulse, as well as estimate the heating augmentation due to that occurrence. A combination of numerical analyses and wind tunnel tests was used to define the heating environment. The wind tunnel tests used phosphor thermography to measure the heating rates on the forebody for a range of freestream conditions. The wind tunnel models featured six cavities of various geometries and locations. Figure 7 is a sample result from these tests, showing the cavities producing different downstream heating augmentations. Based on these re-
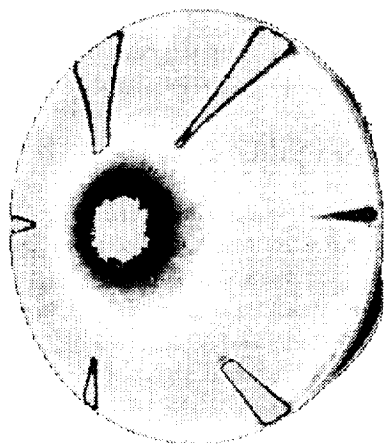
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Figure 7. Sample Genesis SRC thermographic phosphor image.

sults, the cavities are expected to induce transition to turbulence late in the entry (after peak heating). The heating rate downstream of the cavities increases to approximately 750 W/cm^2. The resultant integrated heat load (16.3 kJ/cm^2) is approximately the same as the stagnation value, so sizing the heatshield to the stagnation values is appropriate.

MUSES-C MISSION

The third of a series of science missions managed by the Institute of Space and Astronautical Science of Japan (ISAS) is the Muses-C (Mu Space Engineering Spacecraft) mission.[12,13,14] Muses-C will be the first asteroid sample return mission. Due to a recent change in the mission, the spacecraft is now scheduled to be launched from Kagoshima, Japan in December 2002 for rendezvous with the asteroid 1998 SF 36. This asteroid is a small near-Earth asteroid roughly 1 km in diameter. Once in the vicinity of 1998 SF 36, the spacecraft will fire small pellets into the asteroid and collect the ejecta using a funnel-like device (Fig. 8). The asteroid samples will then be packaged into a sample container for return to Earth in an entry capsule. NASA will participate in the mission by contributing a nano-rover (Fig. 9), in addition to several other aspects of the mission, including mission support and scientific analysis.[15] The tiny rover will be dropped onto the asteroid surface for a one-month tour. Upon Earth return in June 2007, the entry capsule (containing the samples) will be released from the main spacecraft and enter the atmosphere decelerating with the aid of a parachute. The landing site will now be somewhere in the Southern Hemisphere, a change from the prior Northern Hemisphere landing. Although the entry description presented is for a Northern Hamisphere landing, the issues are representative of

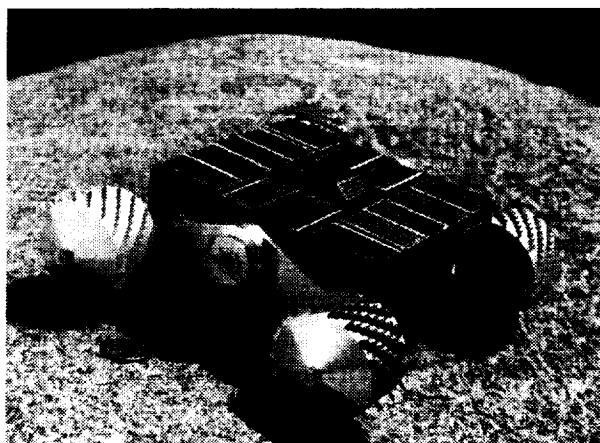*Figure 8. Spacecraft sample acquisition configuration.*

Figure 9. Nano-rover configuration.

those required for one in the Southern Hemisphere. A more in depth mission description and the science objectives can be found at http://www.muses-c.isas.ac.jp.

The Muses-C SRC (Fig. 10) is approximately 0.4 m in diameter having a 45° half-angle sphere-cone forebody and a 30° truncated cone afterbody.[16] Once collected, the asteroid samples will be transferred and sealed into the SRC for Earth return. The forebody heatshield material is a carbon-phenolic ablator. This TPS material was selected to withstand the high forebody heating rates associated with inertial entry velocities greater than 11.0 km/s. The expected peak heating rates (convective and radiative) during entry are in excess of 1500 W/cm^2. Reference 17 gives an overview of the Muses-C SRC thermal protection system.
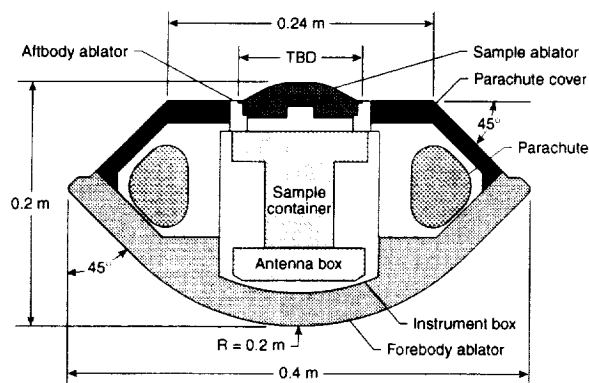
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Figure 10. Muses-C SRC configuration.

The Muses-C SRC is spin stabilized for entry. Upon separation from the main spacecraft, the 18 kg capsule is spun up to 1 rpm. Since the SRC's center-of-gravity location is sufficiently forward, no aerodynamic instabilities exist (in contrast with Stardust and Genesis). As a result, a low spin rate can be utilized since it must provide attitude control only during the period of flight prior to entry. Therefore, the SRC can rely solely on aerodynamic stability for performing a controlled descent through all aerodynamic flight regimes (hypersonic-rarefied, hypersonic-transitional, hypersonic-continuum, supersonic, transonic, and subsonic) without experiencing large angle-of-attack excursions. Furthermore, a stabilizing drogue parachute (which was required for the Stardust and Genesis entries) is not required. As a result, the Muses-C SRC entry sequence (Fig. 11) is fairly straightforward utilizing only a main parachute deploying at approximately 8-10 km (TBD). Upon jettisoning of the aft-cover, the deployment of the main parachute extracts the instrument box (containing the sample container) from the forebody heatshield so that thermal temperature limits are not exceeded. The instrument box continues the descent under parachute until landing. The inertial entry velocity for the Muses-C SRC is approximately
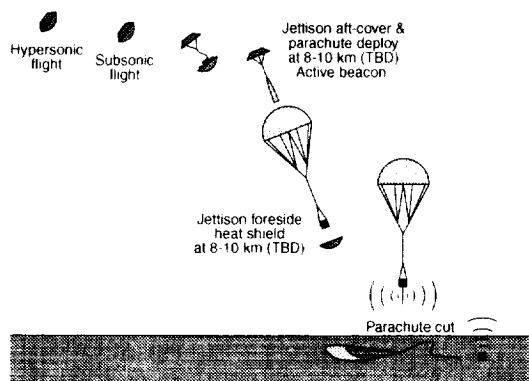

Figure 11. Muses-C SRC entry sequence.

11.6 km/s. The entry flight-path angle is -12.0°, and the peak deceleration during the entry is approximately 45 g's. The landing footprint is roughly 65 km by 20 km.

MARS SAMPLE RETURN MISSION

The Mars Sample Return (MSR) mission will attempt to return the first samples from another planet. The mission is currently in the conceptual design phase. A launch date has not been defined yet, but is being considered towards the end of the coming decade. As presently conceived, the final phase of the mission requires an Earth entry, descent, and landing capsule which is responsible for transporting the samples safely through Earth's atmosphere to a recoverable location on the surface. Preservation of the scientific value of these samples necessitates that they remain isolated from Earth contaminants. In addition, the National Research Council's Task Group on Issues in Sample Return[18] determined that the potential for terrestrial contamination from Mars samples, while minute, is not zero. For these two reasons, stringent requirements will be levied on the Earth entry capsule to assure containment of the samples to very high levels of reliability.[19]

The impact of this requirement on development and design of an Earth Entry Vehicle (EEV) is significant. In fact, the reliability requirement will probably exceed that imposed or obtained by any previous entry system. The design process must incorporate risk-based design strategies and probabilistic risk assessment at every stage. The concept itself must decrease the number of failure modes by eliminating all nonessential subsystems, and utilize heritage systems with sufficient redundancy for each critical subsystem.

A proposed design concept for the MSR Earth Entry Vehicle is described in Reference 20. The design rationale for the capsule's reliability is presented. The concept utilizes a direct entry of a passive capsule that does not include a parachute terminal descent system. Terminal descent of an entry capsule typically includes a parachute deceleration system. Unfortunately, parachute system reliability and that of their activation systems are not adequate to meet the reliability requirements anticipated for this mission. As a result, the EEV relies solely on aerodynamic stability for deceleration and attitude control for descent. The entry capsule must, therefore, be designed to assure containment of the samples in the event of parachute failure. The samples, in such a design, are packaged in hardened container(s) and surrounded by sufficient energy-absorbing material to limit dynamic loading during ground impact. Figure 12 shows a schematic of the EEV.
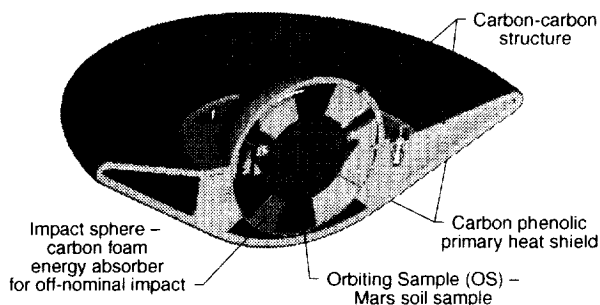
Figure 12. MSR EEV configuration.

The EEV is approximately 0.9 m in diameter and has a 60° half-angle sphere-cone forebody. The sample container is centered within the impact sphere. The high inertial entry velocity of 11.5 km/s drives the design to a blunt aeroshell with an ablating heatshield to protect the vehicle from the intense heating environment. A carbon-phenolic ablating heatshield material is utilized. The peak heat rate (convective and radiative) during the entry is approximately 1500 W/cm². In addition, the 60° half-angle spherically blunted cone forebody provides the appropriate drag and stability characteristics for the descent.

Upon Earth return, the 45 kg EEV is separated from the main spacecraft and spun up to 2 rpm. Since the EEV's center-of-gravity location is sufficiently forward, no aerodynamic instabilities exist. Therefore, the EEV can rely solely on aerodynamic stability for performing a controlled descent through all aerodynamic flight regimes: hypersonic-rarefied, hypersonic-transitional, hypersonic-continuum, supersonic, transonic, and subsonic without experiencing large angle of attack excursions. Upon ground impact, the kinetic energy is absorbed by the ground, by the heatshield, by deformation and failure of the capsule structures, and by crush of the energy absorbing material. Figure 13 illustrates the entry sequence. A fairly steep entry flight-path angle of –25° is used to minimize the integrated head load into the structure. The
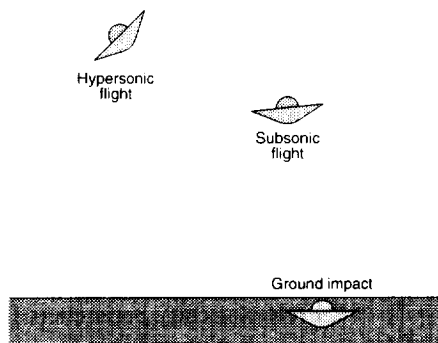

Figure 13. MSR EEV entry sequence.

resulting peak deceleration load is a hefty 135 g's (which is within the capability of the EEV design). The overall landing footprint is approximately 35 km by 15 km.

COMET NUCLEUS SAMPLE RETURN MISSION

Comet Nucleus Sample Return (CNSR) is a comet sample return mission currently under study. Slated for launch near the end of the coming decade, the spacecraft will land on a comet and core a sample for Earth return utilizing an entry capsule. Several target comets (e.g. Brooks 2 Wirtanen, Kopff, Tritton, etc) are available for visitation and sample return depending upon the timeframe of design maturity and readiness of the spacecraft. The mission currently is only in the study phase, so mission requirements have not been defined. However, general mission characteristics have been outlined.

Desire to maintain integrity of frozen comet volatiles in the samples introduces the requirement to maintain the samples at cryogenic conditions throughout the interplanetary flight, and during the Earth entry, descent, landing, and sample recovery. During interplanetary cruise, power will be available to maintain the cryogenic state of the sample container. However, upon Earth return, the passive entry capsule will rely on phase change material for thermal control to maintain the samples at cryogenic conditions. To minimize the amount of phase change material, the thermal load into the capsule must be limited. Consequently, the capsule heatshield must be jettisoned as soon as possible. As currently envisioned, the entry scenario for CNSR would deploy a supersonic drogue parachute at around Mach 2.2 (TBD) to quickly decelerate the capsule to subsonic speeds. Shortly thereafter, the main parachute would be deployed and the heatshield jettisoned to eliminate any further thermal input into the capsule. This event will occur at a fairly high Mach number of around 0.8 (TBD) as compared to any of the previously described missions. A mid-air retrieval of the capsule is performed using a helicopter to allow quick recovery of the samples and subsequent placement into a cryogenic container for storage. A preliminary timeline and conceptual entry scenario is illustrated in Fig. 14.

The Earth return capsule containing the samples will be passive and spin stabilized for entry, similar to all the other sample return capsules described previously. A blunt aeroshell will be utilized having a forebody half-angle sphere-cone of around 60°. Depending upon the comet that is visited, the entry speeds upon Earth return will be in the neighborhood of 14-16 km/s. The high energies associated with these velocities will result in
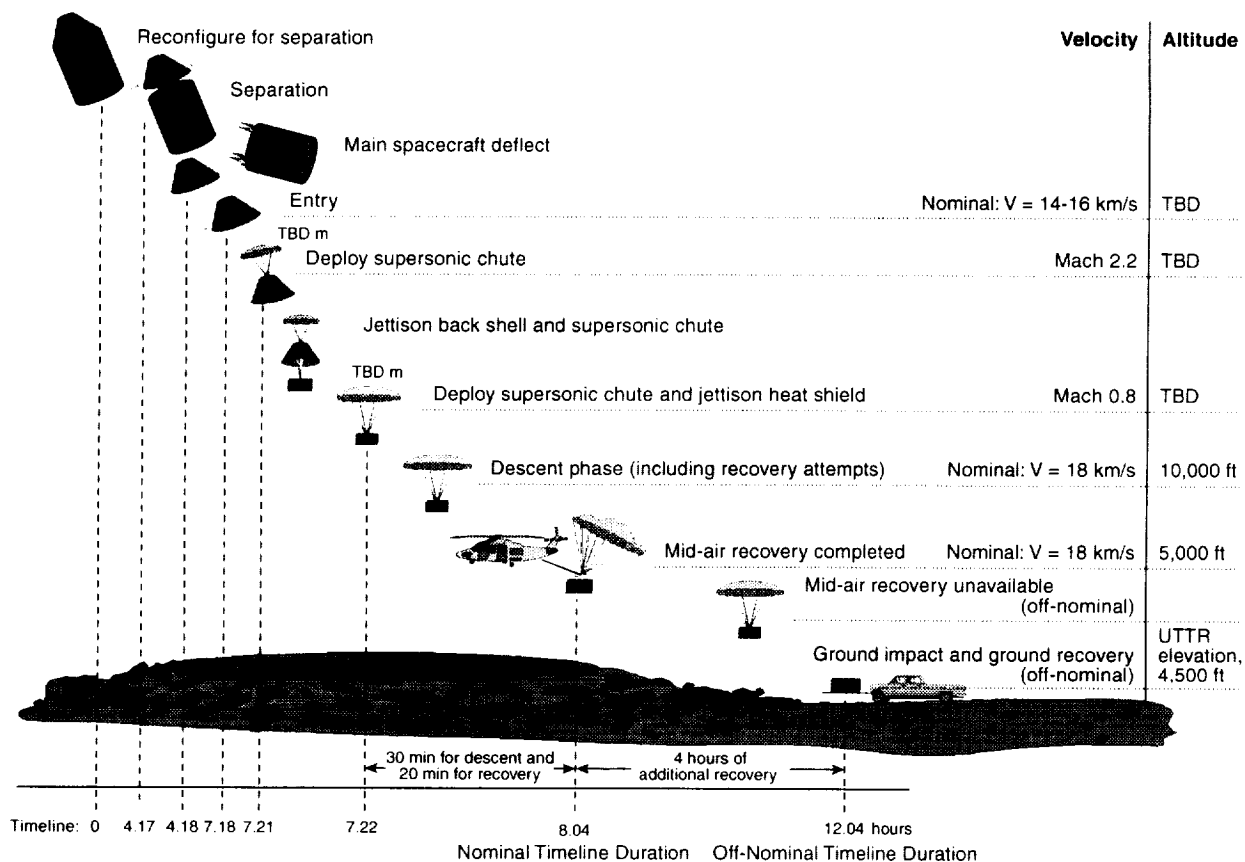
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Figure 14. CNSR capsule entry sequence.

Table 1. Summary of Entry Parameters for sample Return Missions.

	Stardust	Genesis	Muses-C	MSR	CNSR
Mass, kg	46	210	18	45	TBD
Inertial velocity. km/s	12.9	11.0	11.6	11.5	14-16
Inertial flight-path angle, deg	-8.2	-8.0	-12.0	-25.0	TBD
Spin rate, rpm	15	15	2	2	TBD
Peak deceleration, Earth g's	34	28	45	135	TBD
Peak heat rate, W/cm^2	1200	750	~1500	~1500	>>1500
Drogue chute deployment Mach number	1.4	1.8	—	—	2.2 (TBD)
Main chute deployment Mach number	0.16	0.15	~0.25 (TBD)	—	0.8 (TBD)
Landing footprint size, km	60 × 20	55 × 20	~65 × 20	~35 × 15	TBD

peak heating rates well in excess of 1500 W/cm^2. A carbon-phenolic type ablator material will most likely be needed for the heatshield. The high heating environment during the entry will significantly impact the requirements for the passive phase-change thermal control system. In addition, entry deceleration loads will also be fairly high. A considerable trade exists for this mission in terms of the comet visited, the Earth entry velocity (and associated heating rates), and the capsule design. A summary of the relevant entry parameters for all the sample return missions is give in Table 1.

8

SUMMARY

Over the coming decade, several missions will attempt to return samples to Earth from various parts of the solar system. A description of five sample return missions (highlighting the entry, descent, and landing scenario) is presented. A passive, spin-stabilized entry capsule is utilized by all missions. The Earth entry velocities for these missions will be higher to date (greater than 11.0 km/s) of any previous missions. The resulting high energies associated with the entry drives the capsule design to a blunt aeroshell with an ablating heat-shield material for protection from the intense heating environment. Each mission faces unique and different challenges in the design of the entry capsule. The design must address the aerodynamic, heating, deceleration, landing, and recovery requirements to safely return samples to Earth.

REFERENCES

1) The Space Science Enterprise Strategic Plan: Origin, Evolution, and Destiny of the Cosmos and Life, National Aeronautics and Space Administration, November 1997, http://spacescience.nasa.gov/strategy/1997.

2) Willcockson, W., "Stardust Sample Return Capsule Design Experience," *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, May-June 1999, pp. 470-474.

3) Tran, H., Johnson, C., Rasky, D., Hui, F., Chen, Y. K., and Hsu, M., "Phenolic Impregnated Carbon Ablators (PICA) for Discovery Class Missions," AIAA Paper No. 96-1911, June, 1996.

4) Olynick, D., Chen, Y. K., and Tauber, M. E., "Aerothermodynamics of Stardust Sample Return Capsule," *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, May-June 1999, pp. 442-462.

5) Wilmoth, R. G., Mitcheltree, R. A., and Moss, J. N., "Low-Density Aerodynamics of Stardust Sample Return Capsule," *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, May-June 1999, pp. 436-441.

6) Mitcheltree, R. A., Wilmoth, R. G., Cheatwood, F., M., Brauckmann, G. J., and Greene, F. A., "Aerodynamics of Stardust Sample Return Capsule," *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, May-June 1999, pp. 429-435.

7) Mitcheltree, R. A., and Fremaux, C. M., "Subsonic Dynamics of Stardust Sample Return Capsule," NASA TM 110329, March 1997.

8) Desai, P. N., Mitcheltree, R. A., and Cheatwood, F., M., "Entry Dispersion Analysis of the Stardust Sample Return Capsule," *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, May-June 1999, pp. 463-469.

9) Desai, P. N., Mitcheltree, R. A., and Cheatwood, F., M., "Entry Trajectory Issues for the Stardust Sample Return Capsule," Paper No. 15.1, International Symposium on Atmospheric Reentry Vehicles and Systems, March 1999, Arcachon, France.

10) Cheatwood, F. M.; Winchenbach, G. L.; Hathaway, W.; and Chapman, G.: "Dynamic Stability Testing of the Genesis Sample Return Capsule," AIAA Paper 2000-1009, 38th AIAA Aerospace Sciences Meeting & Exhibit, Reno, Nevada, January 2000.

11) Desai, P. N., and Cheatwood, F., M., "Entry Dispersion Analysis of the Genesis Sample Return Capsule," AAS Paper No. 99-469, AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska, August, 1999.

12) Kawaguchi, J., "Nereus Sample Return Mission," *Acta Astronautica*, Vol. 15, No. 5, 1995, pp. 277-284.

13) Kawaguchi, J., Saitoh, H., Uesugi, T. K., and Fujiwara, A., "Muses-C, Asteroid Sample and Return Journey and its Technology Development," Paper IAA 11.2.5, 49th International Astronautical Congress, Melbourne, Australia, September 1998.

14) Kawaguchi, J., and Uesugi, T. K., "Technology Development Status of the Muses-C Sample and Return Project," Paper IAF-99-IAA.11.2.02, 50th International Astronautical Congress, Amsterdam, The Netherlands, October 1999.

15) Jones, R., and Wilcox, B., "NASA Participation in the ISAS Muses-C Asteroid Sample Return Mission," Paper IAF 99-Q.5.03, 50th International Astronautical Congress, Amsterdam, The Netherlands, October 1999.

16) Inatani, Y., Ishii, N., Hiraki, K., and Yamada, T., "Reentry Capsule Design for the Asteroid Sample Return Mission," Paper ISTS 98-I-11, 21st International Symposium on Space Technology and Science, Sonic City, Omiya, Japan, May 1998.

17) Yamada, T., Hiraki, K., Ishiil, N., and Inatani, Y., "Reentry Capsule Design for the Asteroid Sample Return Mission," Paper ISTS 98-d-04, 21st International Symposium on Space Technology and Science, Sonic City, Omiya, Japan, May 1998.

18) Hermann, R. J., and Lineberger, W. C., "Mars Sample Return: Issues and Recommendations," Task Group on Issues in Sample Return, Space Studies Board, National Research Council, ISBN 0-309-057337, National Academy of Sciences, 1997.

19) Adler, M., "The Mars Sample Return Context for Earth Entry, Descent, and Landing," AIAA Paper No. 98-2849, 7th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, Albuquerque, NM, June 1998.

20) Mitcheltree, R. A., Braun, R. D., Simonsen, L. C., and Hughes, S. J., "Earth Entry Vehicles for Mars Sample Return," Paper IAF-00.Q.3.04, 51th International Astronautical Congress, Rio de Janeiro, Brazil, October 2000.